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SUSCEPTIBILITY OF PARAMAGNETIC COPPER-NICKEL ALLOYS

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Wright-Patterson Air Force Base, Ohio

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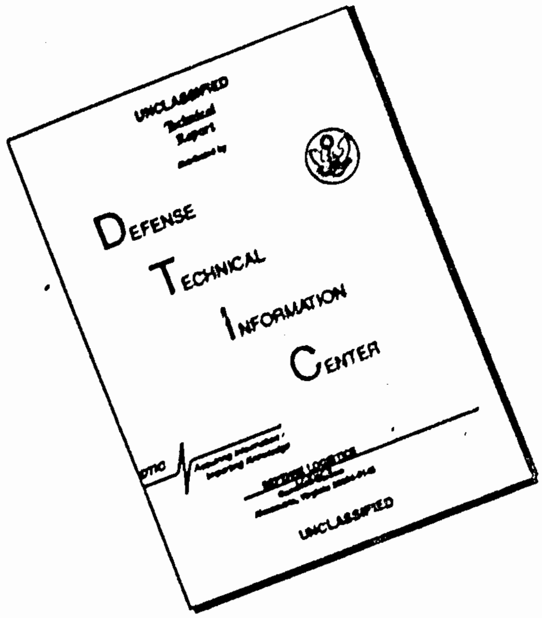

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SUSCEPTIBILITY OF PARAMAGNETIC COPPER-NICKEL ALLOYS

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Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

* <u>ye</u> initially, after vowels, and after ъ, ь; <u>e</u> elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

FOLLOWING ARE THE CORRESPONDING RUSSIAN AND ENGLISH

DESIGNATIONS OF THE TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	$\sin^{-1}$
arc cos	$\cos^{-1}$
arc tg	$\tan^{-1}$
arc ctg	$\cot^{-1}$
arc sec	$\sec^{-1}$
arc cosec	$\csc^{-1}$
arc sh	$\sinh^{-1}$
arc ch	$\cosh^{-1}$
arc th	$\tanh^{-1}$
arc cth	$\coth^{-1}$
arc sch	sech^{-1}
arc csch	csch^{-1}

rot	curl
lg	log

SUSCEPTIBILITY OF PARAMAGNETIC COPPER-NICKEL ALLOYS

[illegible], [illegible],[1] [illegible] Kraynov,
and [illegible]

The field dependence of the magnetic moment of copper-nickel alloys in pulsed magnetic fields having an intensity of up to [illegible] kOe at various temperatures above the Curie point is measured. Six alloys from the critical concentration region were studied. The contribution of magnetic clusters is considered when working out the curves for the dependence of the magnetic moment of the alloys under consideration. The behavior of the clusters in the magnetic field was described by using a Langevin gas model. The experimental curves agree sufficiently well with the theoretical; moreover, the term relating to the clusters is significant. The average magnetic moment in a cluster is equal to [illegible] μ_B, whereas the effective number of clusters per 1 cm^3 is on the order of [illegible]. Quantity $\chi_p(T)$ with respect to the order of magnitude equals 10^{-4} electromagnetic units per cm^3. The large value of susceptibility of the alloys in the region under consideration can be explained by the transition of the system through the critical state when ferromagnetism ceases.

We conducted measurements of the field dependence of the magnetic moment of copper-nickel alloys in pulsed magnetic fields having

[1] [illegible], Institute of [illegible], Berlin (GDR).

an intensity of up to 150 kOe at various temperatures above the Curie point. The Curie temperatures and temperature intervals of the measurements for each alloy are given in the table. Six alloys were studied whose compositions approximated the critical concentration corresponding to the transition of the system from the ferromagnetic to paramagnetic state. The methods used to produce the magnetic field and for measuring were described earlier in [1]. The magnetic moment in the strong field was measured with an accuracy of 2%. All the alloys were subject to homogenizing annealing for 96 h at 1100°C. The uniformity of the alloys was verified by an X-ray microanalyzer. There were less than 0.01% impurities in the samples.

A number of articles [2-4] give the results of measuring the Curie temperature T_c for alloys in the Cu-Ni system. However, in view of the divergence of the data presented relating to the alloys having Curie temperature values from 2 to 40°K, it was necessary to conduct independent measurements of T_c for the samples under consideration. The curve of the dependence of initial susceptibility on temperature obtained in

Numerical values of parameters determined by the method of least squares.*

(1) [illegible]		T_c, °K	ΔT, °K	$C\cdot10^{[illegible]}$	$[illegible]\cdot10^{[illegible]}$	$\chi_d(0)\cdot10^{[illegible]}$	$-\beta\cdot10^{[illegible]}$	$\Delta\chi_d(0)\cdot10^{[illegible]}$	$\Delta\beta\cdot10^{[illegible]}$	μ, μ_B	$N\cdot10^{[illegible]}$, cm$^{[illegible]}$	$\chi'_d(0)\cdot10^{[illegible]}$
Ni	Co											
39,2	60,8	–	4,2–[illegible]	13,5	11,1	13,1	11,0	0,4	0,6	7	7,1	—
43,8	56,2	3,1	6,[illegible]–35,6	11,7	15,3	14,2	10,8	0,4	0,4	7	7,1	—
44,0	[illegible]	3,8	[illegible]–29,1	11,1	19,5	13,6	14,3	1,1	0,8	7	7,1	13
[illegible]	[illegible]	6,6	10,5–[illegible]	11,3	21,1	13,8	15,5	1,4	1,4	7	7,1	11
45,7	54,3	15	27,5–38,7	18,[illegible]	28,5	18,1	15,7	1,7	0,7	7	7,2	12

*Here ΔT is the measurement temperature interval; $\Delta\chi_d(0)$ and $\Delta\beta$ are the dispersions of the corresponding parameters. The quantities whose dimensionality is not indicated are given in electromagnetic units.
KEY: (1) Alloy composition, at. %.

a slightly variable magnetic field was recorded on a two-coordinate curve-drawing instrument. The temperature at which the initial susceptibility achieved its maximum value was identified with the alloy Curie temperature. The T_c values obtained agree well with the data supplied by Robbins, Claus and Beck [2].

The drawing depicts the dependence of the magnetic moment of two samples on the magnetic field at various temperatures. The experimental curves for other alloys have a similar shape. The tendency of the obtained curves toward saturation in the region of large fields, as well as the data of other authors [5] which confirm the presence of the heterogeneous distribution of magneticity in Cu-Ni alloys, makes it necessary to take into consideration the susceptibility $\chi_{\text{кл}}$ which is associated with the magnetic clusters.

The susceptibility of the paramagnetic alloys under consideration in a strong field can, in a way similar to the work of Foner and associates [6], be represented in the form of the following sum:

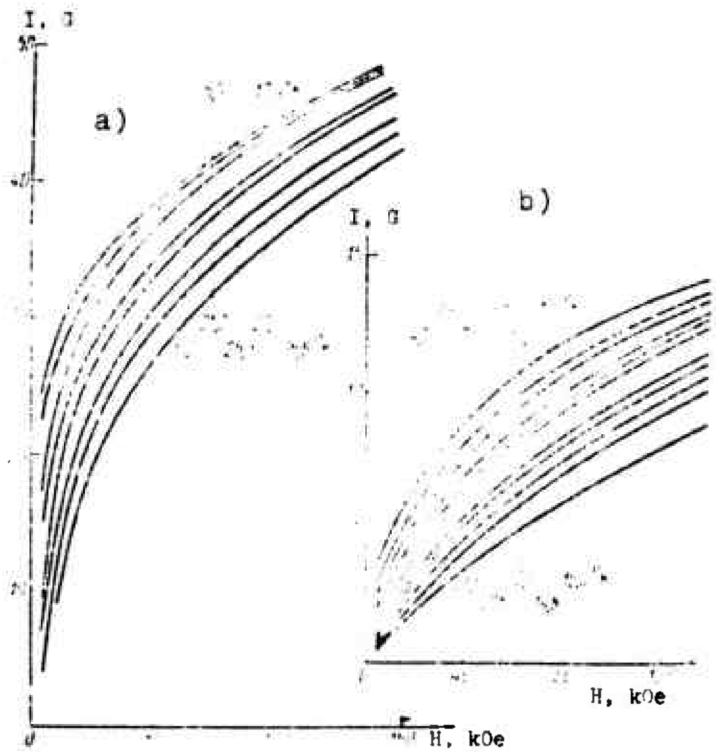
$$\chi = \chi_s + \chi_d + \chi_{vv} + \chi_{\text{диа}} + \chi_{\text{кл}} \tag{1}$$

where χ_s is the Pauli spin susceptibility of the s-electrons; χ_d is the Pauli spin susceptibility of the d-electrons; $\chi_{\text{диа}}$ is the diamagnetic susceptibility of the electrons of the filled shells and conduction electrons, χ_{vv} is the Van Vleck paramagnetic susceptibility. To obtain information concerning the band structure of the alloy being studied it is necessary to isolate the Pauli susceptibility χ_d of the d-band electrons from sum (1). The contribution of χ_s, χ_{vv}, and $\chi_{\text{диа}}$, which enter into (1) can be evaluated.

The paramagnetic susceptibility of the s-band electrons χ_s is $0.9 \cdot 10^{-6}$ electromagnetic units per cm^3 for Ni [6]. Theoretical calculation of the Van Vleck susceptibility χ_{vv} for Ni, accomplished by Shimizu [7], produces the quantity $1.1 \cdot 10^{-5}$ electromagnetic units per cm^3, which agrees also with the estimates made in [6]. We assume that orbital susceptibility of the alloys under study equals the

Van Vleck susceptibility of Ni multiplied by the Ni concentration in the alloy, since the Cu d-band is completely filled and cannot contribute to χ_{vv}.

An evaluation of the diamagnetic susceptibility of the alloys under study can be made on the basis of measuring the magnetic susceptibility of a Cu^{+} ion whose d-band is filled. The measured ionic susceptibility of Cu is $\chi_{дна} = -2.5 \cdot 10^{-6}$ electromagnetic units/cm^3 [8]. Calculation of the diamagnetic susceptibility of Ni [9], which is included in evaluating the entire electron shell of the atom except for 4s-electrons, yields the quantity $-3.3 \cdot 10^{-6}$ electromagnetic units/cm^3. We assume that the experimentally determined diamagnetic susceptibility of the Cu^{+} ion, which equals $-2.5 \cdot 10^{-6}$ el. magn. units/cm^3, can be viewed as the upper limit of $\chi_{дна}$ for the samples under consideration, since the d band in Ni is not filled completely; it is known that the d-electrons specifically make the main contribution to diamagnetic susceptibility.



Dependence of magnetic moment of Cu-Ni alloy at various temperatures: a) sample of 43.8 at. % Ni + 56.2 at. % Cu; b) sample of 39.2 at. % Ni + 60.8 at. % Cu.

Thus,

$$\chi_e + \chi_{vv} + \chi_{dia} \leq 0{,}9\cdot10^{-6} + 1{,}1\cdot10^{-5}\cdot0{,}5 + 2{,}5\cdot10^{-6} \approx 1\cdot10^{-5},$$

and the maximum contribution from these susceptibilities is less than 10% of the experimental susceptibility quantities.

The expression for χ_d has the following form [10]:

$$\chi_d = \chi_d(0)\ (1 + \beta H^2), \tag{2}$$

where

$$\chi_d(0) = 2\mu_B^2 N(\varepsilon_F)\,[1 - J_{eff} N(\varepsilon_F)]^{-1}, \tag{2a}$$

$$\beta = {}^1/_2 \nu\mu_B^2 [1 - J_{eff} N(\varepsilon_F)]^{-3}, \quad \nu = \left[\frac{N''}{N} - 3\left(\frac{N'}{N}\right)^2\right]_{\varepsilon=\varepsilon_F}. \tag{2b}$$

here $N(\varepsilon)$ is the density of the states; J_{eff} is the energy of exchange interaction and ε_F is the Fermi energy.

The average magnetic moment in a cluster is 8-12 μ_B [5], and therefore the behavior of the clusters in the magnetic field can be described using a simple Langevin gas model. The effective field of interaction between the clusters was not taken into account, since the fields in which the investigations were carried out are large. Thus, the magnetic moment related to the presence of clusters can be given in the form

$$M_{cl} = N\mu L\left(\frac{\mu H}{kT}\right) = N\mu\,\mathrm{cth}\frac{\mu H}{kT} - \frac{NkT}{H} \tag{3}$$

where μ is the average magnetic moment in the cluster; N is the effective number of clusters per 1 cm^3; $L(x) = \mathrm{cth}\ x - 1/x$ is the Langevin function; k is the Boltzmann constant.

Consequently, while processing the experimental data the magnetic moment for the Cu-Ni alloys is written as

$$M(H,T) = CH + BH^3 + N\mu\,\mathrm{cth}\frac{\mu H}{kT} - \frac{NkT}{H}, \tag{4}$$

where $C = \chi_e + \chi_{vv} + \chi_{dia} + \chi_d(0)$ is the portion of susceptibility which is independent of the field and temperature, and $B = \chi_d(0)\beta$.

Working out the curves of field dependence of magnetic moment for the alloys for each temperature was accomplished by the method of least squares using a computer. The parameters C, B, N, and μ, and consequently, $\chi_d(0)$ and β, were isolated. The experimental curves are sufficiently described by expression (4), where the term associated with the clusters is important. The average magnetic moment in the cluster was $7\mu_B$, and the effective number of clusters per 1 cm^3 was on the order of 10^{20}. All the parameters changed only slightly with temperature. The average value of the parameters for various temperatures and their mean square deviation from the average value are given in the table. For the sake of comparison the same table gives the values of $\chi_d^f(0)$ obtained for the very same alloys at temperatures below the Curie point [1]. With respect to order of magnitude $\chi_d(0)$ equals 10^{-4} emu/cm^3 - i.e., an order greater than $\chi_d(0)$ for pure Ni, equal to $0.6 \cdot 10^{-5}$ emu/cm^3, and greater than $\chi_d(0) = 3 \cdot 10^{-5}$ emu/cm^3 for an alloy containing 66 at. % Cu [1].

The large value of susceptibility of alloys in the concentration region under study can be explained by the transition of the system through the critical state, when the conditions of ferromagnetism cease to be fulfilled. It was theoretically predicted [11, 12] that susceptibility of alloys must grow with approach of the concentration to the critical concentration, since $(c - c_0)^{-1}$. Precise verification of this proposition is not possible in this article, since the exact value of the critical concentration c_0 is unknown. It is interesting to compare formula (2a) with the Stoner criterion

$$1 - NJ < 0$$

for the appearance of ferromagnetism [13]. Due to the smallness of the denominator in formula (2a) in the concentration region near C_0, it should be expected that there will be large susceptibility values - as were produced experimentally.

The value of the coefficient β with respect to order of magnitude agrees with the estimates obtained from the zone theory

for Pd: $\beta \leq 0.99 \cdot 10^{-11}\ e^{-2}$ [10] but has a minus sign. We see that the Fermi energy of Cu-Ni alloys lies within the region where curvature $N(\varepsilon)$ is small or negative. The experimental value of β for $Pd_{0.95}Rd_{0.05}$ alloys [14] is very close to the value of β which was obtained for Cu-Ni alloys.

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References

[1] A. Plöschke, F. [illegible] Krainov, W. E. Bede, S. A. Finkelberg, Phys. Stat. Sol. [illegible] 10, 22[illegible], 1972.
[2] C. G. Robbins, H. [illegible], P. A. Beck, J. Appl. Phys. 40, 22[illegible], 1969.
[3] A. J. P. Meyer, C. Wolff, [illegible] 2[illegible], 1958.
[4] A. Arrott, Phys. Rev., 10[illegible], 1957.
[5] T. J. Hicks, B. Rainford, J. S. Kouvel, G. G. Low, J. B. Comly, Phys. Rev. [illegible], 22, [illegible]; J. S. Kouvel, J. B. Comly, Phys. Rev. Lett. 24, [illegible], 1970.
[6] S. Foner, A. J. Freeman, N. A. Blum, R. B. Frankel, E. J. McNiff, Jr., H. C. Praddaude, Phys. Rev. 181, [illegible].
[7] M. Shimizu, T. Takahashi, A. Katsuki, J. Phys. Soc. Japan, 18, [illegible], 1963.
[8] [illegible]
[9] J. H. M. Stoelinga, R. Gersdorf, G. de Vries, Physica 41, 457, 1969.
[10] E. P. Wohlfarth, Phys. Lett. 22, [illegible], 1966.
[11] J. M[illegible], Proc. Roy. Soc. [illegible]; J. Mathon, E. P. Wohlfarth, Phys. Stat. Sol. 30, K131, 1968.
[12] C. H[illegible], S. Shtrikman, E. P. Wohlfarth, Phys. Lett. 39A, 87, 1972.
[13] E. C. Stoner, Proc. Roy. Soc. A165, 372, 1938; A169, [illegible], 1939.
[14] S. Foner, E. J. McNiff, Phys. Lett. 29A, 28, 1969.